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Transport of Firebrands by Line Thermals†

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Abstract—The motion of a strong line thermal in an unstratified atmosphere is modeled to estimate a bound for its capability to lift firebrand particles. It is found that the maximum height of a viable firebrand is roughly proportional to the square root of thermal strength. The horizontal distance traveled from the point of origin to the point where free descent begins is calculated for two wind-speed profiles with height, assuming the transporting thermal to be embedded in the windfield. This downwind drift distance is shown to be both significant and sensitive to the windspeed profile.

INTRODUCTION

The job of controlling a wildland fire is often complicated by the phenomenon called "spotting." A fire is said to be spotting when it produces sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire (USDA Forest Service, 1956). In the United States, spotting is cited as the single most vexing problem in fire control (Brown and Davis, 1973), which view might well be endorsed by Australian firefighters (Luke and McArthur, 1978). Other than timely detection of spot fires and prompt suppression action, there is no practical defence against this mode of spread of wildfire.

When fire is used as a land management tool, the prescription of burning conditions, site preparations before ignition, and firing patterns can each be adjusted to minimize the potential for fire escape by spotting. Nonetheless, prescribed fires that escape their intended perimeters frequently do so by spotting.

Recently, models have been advanced that predict the maximum spotting distance to be expected when firebrand particles are lofted by the transitory flames from the burning of a small group of trees (Albini, 1979) or by the persistent flame from a burning pile of fuel (Albini, 1981). These predictive models have found broad application, and have been implemented as programs for handheld calculators for easy field use (Chase, 1981). The hot plume that lifts the firebrand particles was modeled as a classical point source of buoyancy in each case, but in the first instance the transient behavior of the plume was approximated.

Spotting from a line fire has not been modeled, in part because a two-dimensional steady plume leads to predictions of extreme lifting heights of firebrand particles. This occurs because the dynamic presure in the steady, planar plume core decreases only very slowly with altitude (Gostintsev and Sukhanov, 1977, 1978) and even increases with height for a uniform atmosphere (Taylor, 1961; Lee and Emmons, 1961; Turner, 1973; Chen and Rodi, 1980).

The intermittent generation of dense billows of smoke by a wind-aided line fire is frequently observed. These quasi-periodic events likely mark the evolution of thermals.

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Such thermals are analyzed here for their potential to spread fire over distances up to a few kilometers. By retaining the assumptions of a two-dimensional flow field, we are assured that the resulting spot fire distances will be maximal. The thermal is considered "strong" in the sense that its initial density deficiency can be a large fraction of the ambient density, so we do not employ the Boussinesq approximation. The extreme spotting distances of several tens of kilometers sometimes observed on very large wildland fires must be attributed either to aerodynamic firebrands (Luke and McArthur, 1978) or to singular convective phenomena in the nature of fire whirlwinds or "fire storms" (Brown and Davis, 1973), neither of which is addressed here.

FORMULATION

The process envisioned by which spot fires occur can be idealized as a sequence of connected steps. Firstly the main fire must ignite a potential firebrand particle. Before the particle is completely consumed or ceases to burn, it is swept up in the convective activity at or near the flaming front of the fire, and is entrained into the flow that forms a line thermal. As the thermal rises, it is transported downwind by the ambient windfield as a growing coherent structure. The firebrand particle is borne with it, while falling vertically through the thermal's interior. When the particle reaches the lower edge of the rising thermal, it drops out into the ambient windfield to be transported further downwind as it falls. On returning to the surface, it can start a new fire if it retains sufficient energy and falls upon a suitable fuel. This paper is concerned only with the transport of a firebrand particle by the thermal, for which worst-case approximate results are sought.

Aerodynamic properties of potential firebrand particles have been studied (Clements, 1977) and the trajectories of such particles modeled in various flow fields, including the effects of particle combustion (Tarifa *et al.*, 1965; Muraszew *et al.*, 1976; Albini, 1979). The flow fields associated with weak line thermals have been described analytically (Scorer, 1959; Turner, 1973) and measured experimentally (Richards, 1963) and strong two-dimensional steady plumes have recently been studied (Delichatsios, 1981). Strong line thermals have recently been modeled numerically (Luti, 1980, 1981). In this paper we model the behavior of the strong line thermal, idealized as a well-mixed cylindrical structure, in a quiescent unstratified atmosphere. Then the trajectory of a firebrand particle having no aerodynamic lift is calculated, assuming it to be inside the thermal. Finally, we superpose downwind transport by assuming that the thermal structure is embedded in a mean windfield described by a velocity profile with height.

The firebrand trajectory after it leaves the thermal has been described analytically for both logarithmic and power law windspeed profiles (Albini, 1981) including an approximate correction for effects of terrain relief (Albini, 1979). The lofting heights given by the present model can be used to estimate maximum potential spot fire distances using the algorithms in Chase (1981), corrected for downwind drift during lofting.

STRONG LINE THERMAL BEHAVIOR

Treating the line thermal as a right elliptical cylinder of constant shape, filled with thoroughly mixed turbulent hot air, and assuming perfect gas behavior, the conservation laws describing its motion can be written as (see Nomenclature);

$$r^2\rho = r_0^2\rho_0 + (r^2 - r_0^2)\rho_a \tag{1}$$

$$r^2\rho(T - T_a) = E/\pi C \tag{2}$$

$$\frac{d}{dt}(r^2\rho w) = gr^2(\rho_a - \rho) \tag{3}$$

$$\rho T = \rho_a T_a \tag{4}$$

where r^2 has been used for the product of semiaxes ab. Equation (1) expresses the mass of the thermal (all properties of the thermal pertain to a unit length), Eq. (2) its thermal energy, and Eq. (3) the evolution of its vertical momentum. Noting [from Eq. (1)] the constancy of the righthand side of Eq. (3), the vertical velocity equation can be written as

$$\frac{d}{dt}[w\rho/(\rho_a - \rho)] = g. \tag{5}$$

The rate of mass accretion by the thermal can be expressed as the product of ambient air density, the circumference of the thermal cross section and an "entrainment velocity," everywhere normal to the bounding surface of the thermal. For weakly buoyant flows, the entrainment velocity is usually taken to be proportional to the rate of rise of the thermal or the characteristic velocity in a plume (Scorer, 1959; Richards, 1963; Turner, 1973). For strongly buoyant flows, a factor equal to the square root of the density ratio has been included (Morton, 1965) leading to an expression of the form

$$\frac{d}{dt}(r^2\rho) \propto r(\rho_a\rho)^{1/2}w. \tag{6}$$

For simplicity here, we shall neglect the small effect of the density ratio and use a weakly buoyant form that permits analytical solution:

$$\frac{d}{dt}(r^2\rho) = (\eta/\pi)\,2b\rho_a w. \tag{7}$$

Transforming from time to height dependence and assuming the shape of the thermal to be constant (*i.e.*, a/b=constant) leads to the explicit results:

$$(\rho_a - \rho)/(\rho_a - \rho_0) = (r_0/r)^2 \tag{8}$$

$$r = r_0 + (\eta/\pi)(b/a)^{1/2}\, z = r_0(1 + \eta z/\pi a_0) \tag{9}$$

$$\frac{w^2}{2gz(1 - \rho_0/\rho_a)} = \frac{\rho_0/\rho_a + \eta z/\pi a_0 + (\eta z/\pi a_0)^2/3}{[(1 + \eta z/\pi a_0)^2 - (1 - \rho_0/\rho_a)]^2}. \tag{10}$$

The plane $z=0$ has been chosen at the initial height of the centre of the thermal and its initial rise rate has been set to zero.

The asymptotic form of the rise rate with height is

$$\lim_{z\to\infty} w = (\pi a_0/\eta)\,[2g(1 - \rho_0/\rho_a)/3z]^{1/2} \tag{11}$$

which leads to the power law

$$z \sim t^{2/3}. \tag{12}$$

Richards (1963), working with weak cylindrical thermals, found their shapes to be nearly constant and width to vary linearly with distance traveled by the front [Eq. (9)]. He also confirmed the power law of Eq. (12), and his data support the following numerical values:

$$a/b \doteq 0.8 \tag{13}$$

$$\eta \doteq 0.53\pi. \tag{14}$$

Using these figures in Eq. (11) gives the proportionality constant of Eq. (12):

$$\lim_{z\to\infty} \frac{d}{dt}(z + a)^{3/2} = 2.75[\pi r_0^2(1 - \rho_0/\rho_a)g]^{1/2}. \tag{15}$$

Richards' data imply values for the numerical coefficient in this equation from 1.05 to 3.17, with an average of about 1.7. In keeping with the intent of this effort to estimate the maximal capability of line thermals to transport firebrand particles, any bias associated with the slightly high numerical value in Eq. (15) is acceptable.

FIREBRAND TRAJECTORIES

We seek to describe the motion of a small particle being transported by a rising, growing thermal for the purpose of estimating the greatest height to which the thermal can loft it. But the particle is to be a firebrand; that is, it is burning as it is transported, and it must return to the ground before being completely consumed. This requirement imposes a constraint on the amount of burning that can be permitted during the lofting part of the firebrand's flight.

The thermal is assumed to be carried horizontally by a crosswind as it rises, but to maintain its shape (see below). For simplicity, it is further assumed that the motion of the particle in the horizontal plane everywhere mimics that of the thermal, so only its vertical velocity history must be described. Because we wish to make an upper bound estimate of the firebrand lofting capability of a thermal, the initial conditions assumed are that the particle starts at rest, at the top of the vertical extent of the thermal.

Figure 1 shows an end view sketch of the situation modeled here. The elliptical cross-section line thermal is shown in its initial position, part way along its windblown trajectory, and at the instant the firebrand particle exits from its lower boundary. The firebrand particle is indicated by the small filled circle. It begins at rest at the upper surface of the thermal, a distance a_0 above the thermal's center, and exits when its travel ("slip distance") relative to the center of the thermal equals this initial offset plus the distance from the thermal's center to its lower extremity, a_e. The initial

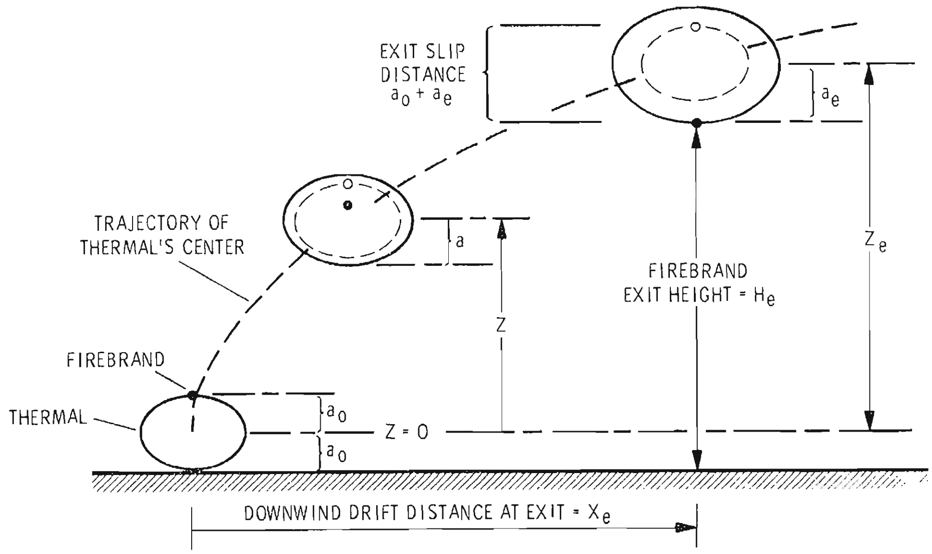

FIGURE 1 Edgeview sketch of sequential positions of an elliptical line thermal in a cross wind showing the relative motion of a firebrand particle lofted by it.

thermal is shown by the dashed outline inside the larger solid figures, with the initial firebrand location indicated by the small open circle. Some nomenclature used is also indicated on this figure, which may be helpful in visualizing several of the relationships developed below.

The burning rate law used here is

$$\frac{d}{dt}(\rho_p D) = -K\rho v. \tag{16}$$

This is the form used in the earlier analyses (Albini 1979, 1981) with the numerical constant value of $K=8.15\times 10^{-3}$. This functional form allows considerable simplification analytically, so it is preferred to alternative expressions that have been proposed (Tarifa *et al.*, 1965; Muraszew *et al.*, 1976; Lee and Hellman, 1970; Steward *et al.*, 1981).

Approximating the air density within the thermal in Eq. (16) as being equal to the ambient value, gives the most rapid decrease in the firebrand particle's mass for a bounding approximation of its vertical acceleration. It also permits immediate integration of Eq. (16) in terms of the relative motion or "slip distance" (s) of the particle and the thermal:

$$\rho_p D \doteq (\rho_p D)_0 - K\rho_a s. \tag{17}$$

This approximation leads to the identification of the maximum slip distance, S, which the particle can experience before it is consumed:

$$S \doteq (\rho_p D)_0 / K\rho_a. \tag{18}$$

The distance S makes a convenient characteristic length, in terms of which the equation for slip velocity and slip distance can be written as:

$$w\frac{dv}{dz} = w\frac{dw}{dz} + g - (C_D/2K)(\rho/\rho_a)(1 - s/S)\,v^2/S \tag{19}$$

$$w\frac{d}{dz}(s/S) = v/S. \tag{20}$$

These equations describe the motion of the firebrand particle relative to the center of the thermal as it rises. The particle falls out the bottom of the thermal at height H_e (see Figure 1); where

$$H_e = z_e - a_e + a_0 = (1 - \eta/\pi)z_e. \tag{21}$$

This occurs when and if the slip distance brings the particle to that boundary, or

$$s_e = a_0 + a_e = 2a_0 + \eta z_e/\pi. \tag{22}$$

In order for the particle to survive to reach the ground, the fall from height H_e plus the slip to distance s_e cannot exceed S. So in addition to the exit criterion of Eq. (22), we have the constraint

$$H_e + s_e = z_e + 2a_0 \leqslant S. \tag{23}$$

From these equations, it is clear that there should exist a particle size (*i.e.*, a value of S) that minimizes H_e without violating Eq. (23). Too small a particle will exit the thermal either not at all or at such a great height that it will be consumed before returning to the ground. Too large a particle will exit at a low height, but return to the surface intact. The particle size that maximizes the spot fire distance will satisfy the equality of Eq. (23) at exit height.

The maximum viable firebrand height that can be provided by a given thermal can be found explicitly in the following manner: The thermal is specified in terms of its initial size (a_0) and density defect ($1-\rho_0/\rho_a$). Fixing these terms specifies the density (ρ) and rise rate (w) as a function of the height of rise (z) of the thermal's center, from Eqs. (8) and (10). Using these forms in Eq. (19) and the values of C_D and K shown in the Nomenclature permits integration of Eqs. (19) and (20) to yield the slip distance (s) as a function of z for any given value of S. At some height z_e the derived value $s(z_e)$ intersects the line $s_e(z_e)$ given by Eq. (22) and the particle exits the thermal. If the particle's height at exit, H_e, satisfies Eq. (23), the particle will survive to return to the surface. Increasing the value of S increases $v(z)$ [Eq. (19)] and so $s(z)$ [Eq. (20)], reducing z_e [Eq. (22)], and vice versa. That value of S which satisfies the equality of Eq. (23) will maximize H_e for the given thermal.

The procedure outlined in the previous paragraph was carried out by numerical integration. To accommodate the square root singularity of $1/w(0)$, the independent variable was transformed to $(z/a_0)^{1/2}$; the variable H_e/a_0 was maximized by trial and error by varying S/a_0, for specified values of $1-\rho_0/\rho_a$. The results of these maximizations are plotted in Figure 2 as max(H_e/a_0)-vs.-$(1-\rho_0/\rho_a)^{1/2}$. The particle size that corresponds to a specific value of H_e can readily be found from Eqs. (22), (23), and (18).

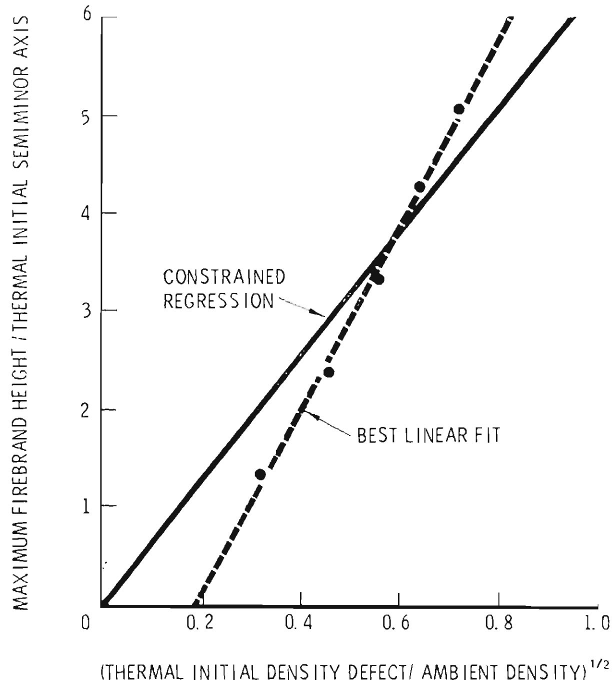

FIGURE 2 Maximum viable firebrand lofting heights achieved for line thermals with various initial density defects.

The best linear equation fit to the data plotted on Figure 2 is graphed over the computed points as a dashed line. This line could serve as a model for the firebrand lofting process, but the solid line, derived by regression with the predictor equation constrained to pass through the origin, is preferred because it eliminates one parameter and greatly simplifies the final result. The constrained regression result is

$$\max(H_e)/a_0 = 6.43(1-\rho_0/\rho_a)^{1/2}. \tag{24}$$

This form is particularly appealing because it reduces to a function of the energy per unit length in the thermal. Using Eqs. (2), (4), and (13), and introducing the ambient pressure P_a explicitly allows Eq. (24) to be written as

$$\begin{aligned} \max(H_e) &= 6.43\,[a_0^2(1-\rho_0/\rho_a)]^{1/2} \\ &= 6.43\left(\frac{0.8}{\pi}\,\frac{\gamma-1}{\gamma}\,E/P_a\right)^{1/2} \\ &= 1.73(E/P_a)^{1/2}. \end{aligned} \tag{25}$$

For example, a thermal with energy of 10^8 J/m would loft a viable firebrand to the maximum height of 55 m according to this result. By way of reference, this thermal strength corresponds to the combustion of approximately 5 kg/m of typical wildland fuel.

DOWNWIND DRIFT DURING LOFTING

The maximum spotting distance downwind from the point at which the particle exits the thermal depends upon the wind profile with height and the shape of the terrain surface over which the particle drifts. The particle trajectories have been calculated and reduced to simple algorithms (Albini, 1979, 1981; Chase, 1981). A correction to the distance so calculated is needed in the present instance to account for the downwind drift of the thermal before the particle drops out of it.

The trajectory of the center of the thermal depends upon the mean windspeed profile with height:

$$u_a(z)=u_a(h)f(z/h), \tag{26}$$

The windspeed profile has a characteristic scale height, h, which can be set equal to the vegetation cover height when significant cover exists. In such cases, the neutral windspeed profile is usually logarithmic (Monteith, 1973) with the following form (Baughman and Albini, 1980) for $z>h$, measured from the surface:

$$f(z/h)=\ln[(z/h-0.64)/0.13] \tag{27}$$

when the terrain over which the thermal drifts is not covered with tall vegetation such as shrubs or trees, the scale height h becomes small and a power law windspeed profile is often used (Sutton, 1953; Plate, 1971)

$$f(z/h)=(z/h)^n. \tag{28}$$

With this form, any height can be used for a reference condition, but the choice of origin is clearly relevant.

The thermal can experience substantial shear due to the difference in windspeed over its vertical extent. This complication has been ignored in the development to this point by the implicit but not necessarily valid assumption that the thermal is everywhere small compared to the vertical length scale of the windspeed profile. But rather than introduce unwarranted exactitude and complexity into the simple, approximate model in hand, we shall seek a bounding estimate for the downwind drift by persisting in this approximation. To find a bounding expression for the downwind drift of the firebrand during lofting, we calculate the drift of the center of the thermal using the asymptotic form (Eq. 11) for its rate of rise and the windspeed at the height of the center. The combination of the overestimate of horizontal windspeed and the underestimate of vertical speed wil be partly compensated by taking the origin of windspeed profile and the center of the thermal to be at the same height. The result will still overestimate, but should give the proper order of magnitude for the downwind drift during lofting. The trajectory is thus to be found from

$$\frac{dx}{dz} \doteq u_a(z)/w(z). \tag{29}$$

Invoking the approximations listed above, Eq. (21), and Eq. (24) in Eq. (11), it is readily shown that the downwind drift distance is given by

$$x_e \doteq 6.43 \, \frac{\eta}{\pi} \left(\frac{3H_e}{2g}\right)^{1/2} u_a(h) \int_{\varepsilon}^{1/(1-\eta/\pi)} \theta^{1/2} f[(H_e/h)\theta] d\theta \tag{30}$$

where ε is the value of θ that brings the windspeed to zero. For the power law profile [Eq. (28)], the particle exit height can be used for a reference condition giving

$$x_e \doteq 6.43 \, \frac{\eta}{\pi} \, \frac{2}{3+2n} \, u_a(H_e) \left(\frac{3H_e}{2g}\right)^{1/2} /(1-\eta/\pi)^{3/2+n}. \tag{31}$$

Using Eq. (14) and the often used exponent $n = 1/7$ gives

$$x_e \doteq 8.8 u_a(H_e)(H_e/g)^{1/2}. \tag{32}$$

Using the example firebrand height of 55 m from above, note that a windspeed of 10 m/s at that height would add about 200 m to the spotting distance . From the power law windspeed profile used, the wind at head height (say 2 m) would be sensed at 6.2 m/s. Such a gentle gradient of windspeed with height strengthens the approximation of shear-free thermal growth.

If the windspeed profile is logarithmic with height, Eq. (30) can be expressed in closed form as

$$x_e/u_a(h)\,(H_e/g)^{1/2} = 6.43(\eta/\pi)\,(2/3)^{1/2}(0.64h/H_e)^{3/2} F \left[\frac{H_e}{0.64(1-\eta/\pi)h}\right] \tag{33}$$

where

$$F(x) = x^{3/2} \left\{ \ln\left[\frac{0.64(x-1)}{0.13}\right] - 2/3 \right\} - 2x^{1/2} + \ln\left(\frac{x^{1/2}+1}{x^{1/2}-1}\right). \tag{34}$$

Again using Eq. (14) and dropping terms of order h/H_e (recall that here h is the vegetation cover height) this reduces to

$$x_e/u_a(h)(H_e/g)^{1/2} = 8.64[\ln(H_e/h) + 2.13]. \tag{36}$$

For comparison with Eq. (32), again consider the example above, with $H_e = 55$ m. Assuming a 2 m cover height and a windspeed at that level of 6.2 m/s, Eq. (36) gives a downwind drift distance of 684 m, or more than three times the power law profile distance. Obviously the windspeed profile can have a profound influence on this quantity.

DISCUSSION

The capability of strong line thermals to lift and transport small firebrand particles has been analyzed in approximate fashion. The height at which a viable firebrand particle exits from the growing, rising thermal was found to be approximately proportional to the square root of the energy per unit length (or strength) of the thermal. This finding stems in part from the approximation that the burning rate of a firebrand is proportional to its rate of air mass displacement.

The thermal drifts downwind as it rises, so the firebrand particle may be transported a significant distance before it exits the thermal. The distance traveled from the point of origin of the thermal to the point at which the firebrand falls out of it is shown here to be an important additive term that is sensitive to the windspeed profile with height.

A notable deficiency in this presentation is the lack of any experimental data with which to compare the predictions of the model. But these results would find application in the prediction of maximum spot fire distances to be expected, given the fuel being burned, windspeed, vegetation cover, and terrain description. A model that permits using field-observable variables to estimate the strengths of thermals generated by a line fire in typical surface fuels has been devised. This model, with the results given here, permits the rapid estimation of maximum spot fire distances† under field conditions. It will soon be available for testing by wildfire control personnel.

NOMENCLATURE

a	semiminor (vertical) axis of elliptical cross section thermal
b	semimajor (horizontal) axis of elliptical cross section thermal
C	specific heat capacity of air (at constant pressure)
C_D	mean aerodynamic drag coefficient for firebrand particle (1.2)
D	characteristic dimension of firebrand particle=volume/reference area for aerodynamic drag
E	thermal's energy per unit length
f	function describing windspeed profile with height
g	acceleration of gravity
H	height
h	characteristic scaling height for windspeed profile
K	dimensionless firebrand burning rate parameter, Eq. (28) (8.15×10^{-3})
n	exponent for power law windspeed profile
P	pressure
r	$\sqrt{(ab)}$
s	particle "slip distance" relative to fluid of thermal
S	slip distance at which particle is completely burned up
t	time, from instant of creation of thermal
T	temperature
u	horizontal velocity
v	fluid velocity relative to firebrand particle (slip velocity)
w	vertical velocity
x	horizontal distance
y	shorthand for $\eta z/\pi a_0$, dimensionless height
z	vertical distance

†Albini, F. A. (1983). Potential spotting distance from wind-driven surface fires, USDA Forest Service Res. Pap. INT (in process), Intermountain Forest and Range Experiment Station, Ogden, UT.

Subscripts

- a ambient
- e evaluated at firebrand exit from thermal
- 0 initial conditions (for thermal, firebrand)
- p firebrand particle

Greek letters

- ρ mass density
- η entrainment factor (0.53π)
- γ ratio of specific heats for air (1.4)

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